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Flow Simulation of Patent Ductus Arteriosus to Evaluate Thrombosis Factors on Closure Device

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ABSTRACT

Patent Ductus Arteriosus (PDA) is one of the most common congenital heart defects that are treated with minimally invasive surgery using occlusion devices. The occlusion device act as a physical barrier to blood flow in the duct which facilitates thrombogenesis and occludes the duct. Over the past 15 years, there have been significant developments in the devices used to close PDA. Various design of occlusion device affects the flow of blood in the duct. To improve an efficiency of the thrombogenesis on the surface of occlusion device and estimate the time needed to occludes the duct, it is important to simulate blood flow through different design of occlusion device. Two design were used which is concave and convex shape of occlusion device. Blood was simulated as Newtonian with laminar flow. The simulation using a computational fluid dynamics (CFD) software showed that velocity and pressure around the convex shape were much lower compared to concave shape. The percentage of WSSlow on the surface of convex shape was 84.3% while only 22.2% on the concave shape. From the preliminary work on PDA occlusion device, it is suggested that to promote thrombosis, convex shape was much better compared to concave shape.

INTRODUCTION

Congenital Heart Defects (CHD) is an abnormality in heart structure present since birth. With this condition, some part of the heart does not form properly. This will change the normal flow of the blood through the heart. There are many types of congenital heart defects. Patent Ductus Arteriosus (PDA) is one of the common heart defects that can occur soon after birth (Figure 1.). In children who were born at term, the incidence of PDA has been reported to be roughly 1 in 2000 births (S. Liddy et al., 2013 and T. Forbes et al., 2012). PDA accounts for around 5% to 10% of all congenital heart defects and is a common problem occurred in preterm infants (Watterberg KL et al, 2016). In PDA, it contributes to abnormal blood flow between two major arteries in the heart which is aorta and pulmonary artery. Before birth, these arteries were connected by a blood vessel called ductus arteriosus as an essential part of fetal blood circulation. The ductus arteriosus should be closed right after birth.

However, if the duct stays open, it will allow oxygen-rich blood from the aorta to mix with oxygen-poor blood from the pulmonary artery. This can strain the heart and increase blood pressure in the lung arteries. In order to meet body oxygen demand, the heart is going to have to pump more blood to cover what circulates in the shunt as well as what the body needs. Therefore, extra work needed for the heart and failure can result, leading to coughing, weakness, and difficulty of breathing. If the size of the PDA is too large, it also can cause death and heart failure. These effects due to the irregularity of the blood transmission occur since the oxygenated blood from the aorta and the deoxygenated blood is mixing.

There are few ways to treat this PDA, patients might take medicines, undergo surgery or using the catheter based procedure. The most popular treatment is using the catheter since it takes a shorter time to recover and will not leave scars on the chest. A closure medical device will be implanted into the patient by using surgical method or by using a transcatheter device. From 1967, Porstmann's first publication according to the non-surgical transcatheter closure was generally accepted by the public from all over the world. Through the years, there are many designs of non-surgical devices that had been used such as Raskind's umbrella, Sideris buttoned device, Embolization coils and Amplatzer Duct Occluder (ADO). Amplatzer Duct Occluder (ADO) is the first device approved specifically for the treatment of PDAs (Moore JW et al., 2005).

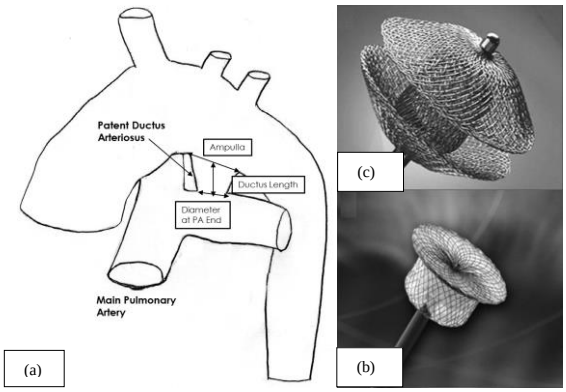

Fig. 1 (a) Patent Ductus Arteriosus (PDA) (b) Amplatzer duct occluder device (AGA Medical Corporation, Plymouth, MN) (c) Amplatzer PDA Duct Occluder II (AGA Medical Corporation, Plymouth, MN). (Douglas J et al., 2012)

The basic principle of occlusion or closure involves introducing a physical barrier to flow of blood in the duct, which is done by implanting the device in the duct. Besides acting as physical barrier, the device also facilitates the process of thrombosis. Thrombosis is a clotting process for the blood. The thrombosis occurrence is important

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after implanting the closure device because it will hold the device tightly and avoid the reopening of the closure device occurred. The clot, with the device in its core, acts as a natural permanent plug and effectively occludes the duct. Therefore, the thrombosis factors can be used to determine the effectiveness of the design of closure device. The low fluid velocity and the resultant low shear stress (< 0.5 Pa) that acts on the wall can be used as the major hemodynamic factors that prone to thrombosis formation. (Asakura T et al., 1990). The thrombosis has been reported, occurred mainly due to the presence of low shear stresses. (Haruguchi H et al., 2003).

Various designs with several size and shape of the devices can influence the flow of the blood in the vessel. Therefore, an analysis is needed on the hemodynamic effects after implanting the device into the PDA. Two designs of closure device attached on the aorta will be simulated using computational fluid dynamic (CFD) software. This study aim was to analyze the hemodynamics flow around the proposed devices. Velocity, pressure and wall shear stress parameters are believed play a key role that affects the thrombosis formation around the devices and thus were used as performance indexes.

METHOD

Computer Aided Design (CAD) software, Solidworks, was used for modelling the simplified model of the PDA. While, CFD was used for simulation of blood flow through the PDA using ANSYS 14.0 FLUENT. Blood was simulated as Newtonian and laminar flow with Reynolds number 1200. The density of blood is 1060 Kg/m^3 and dynamic viscosity 0.005 PaS. Blood was also simulated as steady flow with inlet velocity 0.4796 m/s at ascending aorta and zero pressure outlet at the descending aorta. The flow rate of the blood in the vessel is 3.254 Liter/minute.

The simulations were performed for two different shapes of PDA closure device which are convex and concave**.** Figure 2(a) shows a simplified model of the normal condition of the aorta with concave shape PDA closure device, while Figure 2(b) shows model with convex shape PDA closure device. The dimensions of vessels are shown in Table 1. Three hemodynamics parameters which are velocity, pressure and wall shear stress were evaluated to analyse the factors prone to thrombosis.

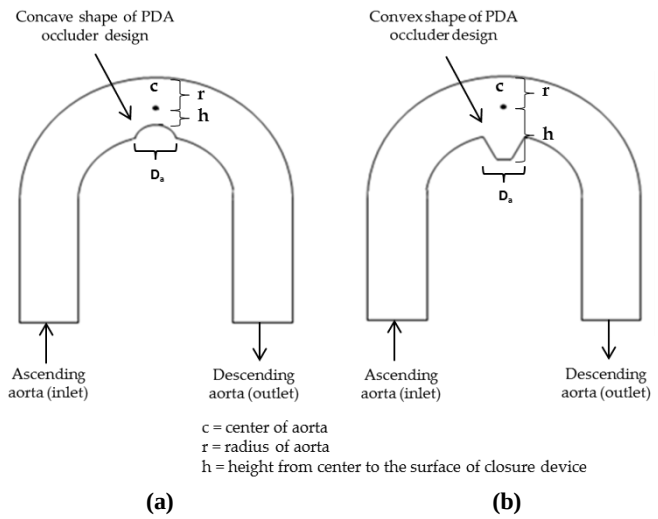


Fig. 2 Closure device occluded the PDA in aorta (a) Concave shape (b) Convex shape

Table 1 Dimensions of aorta and closure device.

Vessel	Dimension (mm)
Diameter of ascending aorta	12
Diameter of descending aorta	12
Ampulla diameter (D_a)	10
Distance, h (Concave)	2.5
Distance, h (Convex)	8.5

RESULTS

A simple geometric model has been proposed for two designs of PDA closure device. Flow simulation was implemented and preliminary results were obtained.

Velocity

Table 2 shows the velocity data at point *f*, for both designs concave and convex shape.

$$f = \frac{Distance, h}{Radius, r}$$

The radius of aorta, r is 6 mm (Thomas K et al., 2008). The total distance, h from center of aorta to the surface of concave shape closure device is 2.5 mm. Three data points were taken along the distance and it is shows that the velocity was reduced a little bit from 0.50 m/s to 0.37 m/s. On the other hands, total distance, h for convex shape is 8.5 mm. Nine data points were taken along the distance and it is shown that the velocity was also reducing and approaching to zero from 0.50 m/s to 0.00 m/s. Figure 4 shows the velocity vector around the closure device for both concave and convex shape. Flow separation was observed at the back of concave shape as in Figure 5(a). However, in Figure 5(b) shows the flow separation within the convex shape. These flow separations indicate the velocity at that point were very slow approaching to zero. These data are represented in Figure 4, the comparison of velocity between concave and convex shape.

Table 2 Velocity Data.

f	Velocity (m/s)	
	Concave	Convex
0	0.50	0.50
0.17	0.43	0.35
0.33	0.37	0.31
0.50		0.29
0.67		0.23
0.83		0.11
1		0.01
1.17		0.02
1.33		0.00

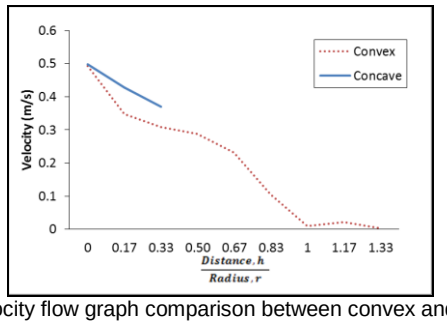
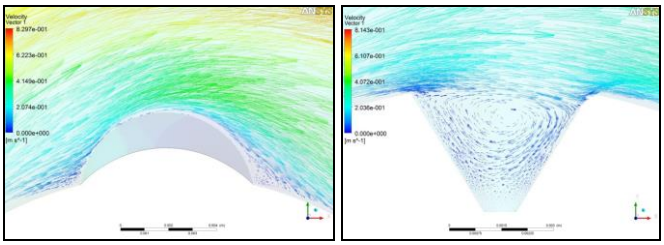


Fig. 4 Velocity flow graph comparison between convex and concave shape of PDA closure device.



(a) (b)

Fig 5. Velocity vector around the closure device (**a**) Concave (**b**) Convex

Pressure

Pressure data are shown in Table 3. It represents in Figure 6 that illustrates that for concave shape, pressure is lower than convex shape. Furthermore, the pressure for both design concave and convex shape were reduced from the center of the aorta to the surface of closure device. The pressure data in concave shape was reduced from 82.26 Pa to 27.98 Pa. While, in convex shape, the pressure was also reducing from 116.66 Pa to 79.22 Pa. These also represent in Figure 7(a) and Figure 7(b) that shows the pressure contour on the sagittal plane view. On the other hand, Figure 8. shows the pressure contour on the wall of PDA closure device for both concave and convex shape. In concave design, the pressure attack at the front point of the wall was higher than at the back of the wall. While for convex design, the flow was directly attacked at the right back of the wall. It caused the pressure at that point higher.

Table 3 Pressure Data.

f	Pressure (Pa)	
	Concave	**Convex**
0	82.26	116.66
0.17	59.31	103.42
0.33	27.98	95.26
0.50		88.19
0.67		81.57
0.83		78.81
1		78.54
1.17		79.10
1.33		79.22

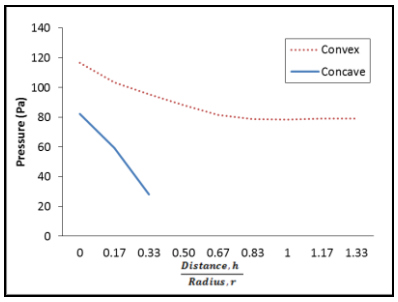
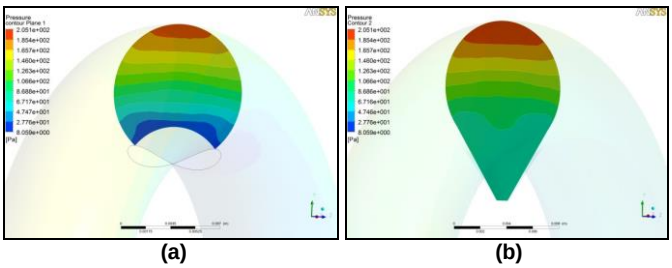
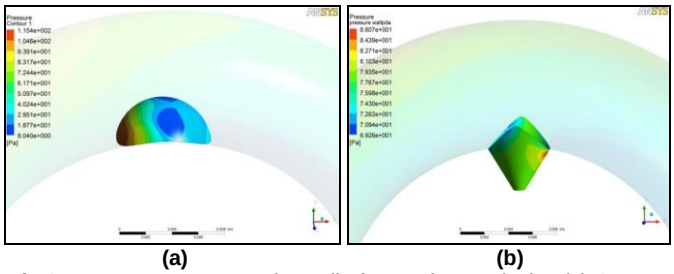


Fig. 6 Pressure flow graph comparison between convex and concave shape of PDA closure device.



(a) (b)

Fig 7. Pressure contour on the sagittal plane (a) Concave (b) Convex



(a) (b)

Fig 8. Pressure contour on the wall of PDA closure device (a) Concave (b) Convex

Wall Shear Stress

Figure 9 shows the contour of wall shear stress (WSS) for both concave and convex shape of PDA closure design. The blue contour shows a low magnitude of wall shear stress. It is clearly shown in the figure that more low magnitude of WSS appeared on the convex shape compared to the concave shape. Low wall shear stress, WSS_{low} (< 0.5 Pa) are one of the hemodynamic factors that plays an important role in formation of thrombosis. Figure 10 shows the graph comparison on the percentage of WSS_{low} for both designs. It is shown that convex shape yielded more WSS_{low} (< 0.5 Pa) magnitude compared to concave shape. From the calculation, the percentage of WSS_{low} in convex shape was 84.3%, while only 22.2% for the concave shape.

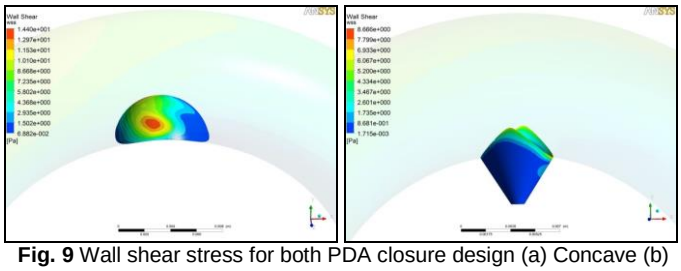


Fig. 9 Wall shear stress for both PDA closure design (a) Concave (b) Convex.

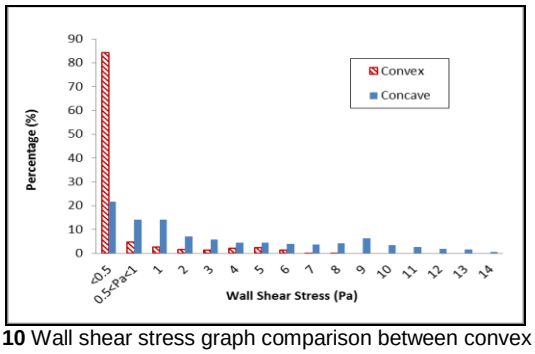


Fig. 10 Wall shear stress graph comparison between convex and concave shape of PDA closure device.

DISCUSSION

Concave and convex shape closure device were designed to close the Patent Ductus Arteriosus (PDA) found on the aorta. Both designs have been compared to evaluate the hemodynamics flow around the closure device to determine the effectiveness of the device on promoting thrombosis formation. Velocity, pressure and wall shear stress were used as the hemodynamics factors that prone to thrombosis formation.

From the analysis, the design of convex shape have increased and promoted the flow separation inside the convex shape. Compared to concave shape, the streamlined shape reduced the flow separation generated around the device. The flow separation was only found at the downstream of concave shape. Therefore, the velocity around the surface of convex shape was very slow and approaching to zero compared to concave shape of closure device. However, pressure is

inversely proportional to velocity as per Bernoulli principles and pressure also increases linearly with increasing of depth. In this case, the depth of the surface of convex shape is deeper than concave shape as shown in Figure 7. Thus, the pressure flow around the convex shape was higher than concave shape and adverse pressure gradient occurred in the direction of flow separation. Furthermore, the flow was directly attacked at the back side of the concave wall, which caused the pressure at that point to increase. It can be assumed that when the blood flow velocity is very low, it will cause a blood to be clot much faster around the closure device. Hence, convex shape can promote thrombosis to occur much faster compared to concave shape.

Correspondingly, the flow recirculation zone indicated that convex shape yielded lower low wall shear stress (WSS_{low}) magnitude compared to concave shape. The flow recirculation zones with WSS_{low} (<0.5 Pa) are connected with inhibition of re-endothelialization, that are potential in enabling pro-coagulant and pro-inflammatory elements to accumulate (Juan MJ et al., 2009), which contribute to thrombosis formation. From the calculation, the percentage of WSS_{low} on the wall of PDA closure device for convex shape was 84.3%, while only 22.2% on the concave shape. Therefore, convex shape was better than concave shape because thrombosis has been reported, occurred due to the presence of WSS_{low}.

The mechanism of occlusion of the PDA is thrombosis formation around the materials of the devices, followed by neo-endothelial growth and cellular organization of the thrombotic material. (Yingying H et al., 2014) It is also important for the device to be anchored firmly in position. Therefore, the size and shape of the devices play an important role in designing an effective closure devices. Contact friction between device and vessel wall also plays a crucial role in anchoring the device. As compression of device increases, friction requires to retain it will be decreased. Larger differential pressure and lesser compression will eventually need higher friction values to retain the device. (Vaibhavi AS et al., 2016)

CONCLUSION

In conclusion, more flow recirculation zones with WSS_{low} (<0.5 Pa) will enable accumulation of pro-coagulant and pro-inflammatory elements that contribute to thrombosis formation. The presence of low blood flow velocity also assumed to cause blood clotting process much faster around the closure device. Hence, convex shape of closure device meets the parameters needed much better than concave shape. Therefore, it is suggested that convex shape of closure device can promote thrombosis much faster compared to concave shape.

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REFERENCES

Asakura T, Karino T. 1990. Flow Patterns and Spatial Distribution of Atherosclerotic Lesions in HumanCoronary Arteries. *Circ Res*. 66, 1045-1066

Douglas J, Schneider, MD. 2012. The Patent Ductus Arteriosus in Term Infants, Children, and Adults. *Seminars in Perinatology* 36, 146-153.

Forbes T, Turner D. 2012. What is the optimal device for closure of a persistently patent ductus arteriosus? *Progress in Pediatric Cardiology*. 33, 125-129.

Haruguchi H, Teraoka S. 2003. Intimal hyperplasia and hemodynamic factors in arterial bypass and arteriovenous grafts: A review. *J Artif Organs* 6, 227-235

Juan MJ, Peter FD. 2009. Hemodynamically Driven Stent Strut Design. *Annals of Biomedical Engineering.* 37, 1486-1494

Liddy S, Oslizlok P, Walsh KP. 2013. Comparison of the results of transcatheter closure of patent ductus arteriosus with newer amplatzer devices. *Catheterization and cardiovascular interventions* 82, 253-259.

Moore JW, Levi DS, Moore SD, et al. 2005. Interventional treatment of patent ductus arteriosus in 2004. *Catheter Cardiovasc Interv* 64, 91–101

Portsman W, Wierny L, Warnke H. 1967. Closure of persistent ductus arteriousus without thoracotomy. *Ger Med Mon* 15, 109-203

Vaibhavi AS, Jayesh RB. 2014. Flow simulation of cardiac defects to evaluate effectiveness of occlusion devices. *Journal of Medical Devices*. Vol. 8

Vaibhavi AS, Jayesh RB. 2015. Simulation of pulsatile blood flow through various cardiac defects and quantitative measurements of shunted blood volume. *Procedia Materials Science* 10, 706-713

Vaibhavi AS, Jayesh RB. 2016. Mathematical modeling and simulation of an occlusion device in a blood vessel. *Cardiovascular Engineering and Technology*. Vol. 7, No. 4, 420-431

Watterberg KL, Aucott S, Benitz WE, Cummings JJ, Eichenwald EC, et al. 2016. Patent Ductus Arteriosus in Preterm Infants. *Pediatrics.*137(1): e20153730

Yingying H, Jen FK, Subbu SV. 2014. Biomaterials and design in occlusion devices for cardiac defects: A review. *Acta Biomaterialia* 10, 1088-1101

Thomas K, Christian JK, Manuela A, Eva B, Emanuela RB. 2008. Normalvalues for aortic diameters in children and adolescents – assessment *in vivo* by contrast-enhanced CMR-angiography. *J Cardiovasc Magn Reson*. 10(1): 56.